Australian Academy of Science

NATIONAL COMMITTEE FOR
SPACE AND RADIO SCIENCE

Australia in Space: a decadal plan for Australian space science

CONSULTATION DRAFT AUGUST 2021

www.science.org.au/australiainspace

Australia in Space: a decadal plan for Australian space science

1. Executive summary

'Human knowledge and human power meet in one.' Francis Bacon

Now is an exciting time to be involved with space. Increasingly diverse and open-market participation in space activities is catalysing transformative opportunities but also amplifying risks. Space-derived activities and services are integral to Australia's economic, social and national security. Australia aims to exploit new opportunities by growing an internationally competitive space industry which will also build innovation capability and address strategic needs. Key to this is a sustainable space sector built on a foundation of excellence in science and technology.

Space science – the science of exploration and use of space to generate new knowledge, disruptive innovation, and practical benefit – is a fundamental enabler for space industry and applications. It underpins the space programs of our partners and our own space aspirations. Australian space science research has established a world class reputation in many areas. It engages with international space programs and is critical for growing our space capability and mitigating risks. However, there is no national commitment or funding for space science research, and no space program. This hinders the sustainable development and competitiveness of our space economy.

This Plan outlines strategies to advance Australia's interests and priorities in space, enabling a vision that sees Australia participating in the global community of spacefaring nations while growing the innovation economy, developing sovereign capability, and improving the lives of all Australians.

To achieve this vision, this Plan makes the following headline recommendations.

1. A national research priority in space science is needed that aligns with civil and defence sovereign industry capability requirements, and to encourage discovery, innovation and help build capacity for national benefit and international impact.

2. A respected voice is needed to represent and support engagement of Australia's space science expertise with the diverse elements of the space sector, and provide a point of contact for collaboration on science missions with other agencies. This should take place through a Lead Scientist within the Australian Space Agency with responsibility for space science policy settings.

3. Commitment to and investment in an ongoing national space program, enabled by space missions which advance science, stimulate technical innovation, address national priorities, grow capability, and inspire citizens.

These headline recommendations underpin our Plan, and are supported by five further recommendations, which seek to develop:

4. An integrated national space innovation and education strategy, led by the Australian Space Agency, that is consistent with the national curriculum, spans the primary, secondary, tertiary, VET and industry sectors, and aims to grow STEM participation, improve career pathways, and improve industry outcomes, cognisant of the values of diversity and gender equity.

5. An ongoing Earth observation satellite program to mitigate data supply risk, address grand national challenges, grow capacity, and contribute to global programs. As part of this Australia should lead international efforts on global instrument and data calibration and validation. This program should be led by the Australian Space Agency.

6. An integrated program to advance basic and applied research on transformative technologies in secure, high bandwidth RF and optical communications technologies including across satellite networks, advanced on-board processing, and next generation secure positioning, navigation and timing (PNT) capabilities. This should include technology demonstrator satellite missions and associated ground infrastructure.

7. A national program focusing space weather research activities to help protect critical infrastructure and advance space weather forecasting and space situational awareness activities. This program should be supported by observations from a diverse and extensive suite of sovereign ground- and space-based sensors.

8. A commitment of support to space life science research, including space medicine and human factors, engaging with international programs and providing translation of research to improve everyday life.

This Plan will position Australia to grow opportunity, productivity, skilled employment, sovereign capability, and protect critical assets, as the global space ecosystem evolves and transforms.

Successful implementation of the Plan will result in a range of benefits, including:

- a sustainable national space science program
- enhanced innovation-led growth of the space economy
- more effective science-to-industry partnerships across the space sector
- sovereign capability to develop and operate small and medium satellite space missions
- ability to collaborate and contribute substantively to transnational missions
- an Earth observation program addressing national challenges and providing international leadership
- world-leading space weather forecasting helping protect critical infrastructure and contributing to space situational awareness capability
- next generation space-based communications and secure PNT services
- improvements in telehealth delivery and health outcomes
- enhanced STEM engagement and workforce capability.

2. Space for Australia

'Somewhere, something incredible is waiting to be known.' Carl Sagan

2.1 Objectives

Australia's economic, social and national security depend on space-derived services and capabilities[1]. They enable our communications and data networks, environmental monitoring and management, weather forecasting and emergency services, positioning information for transport, automation and logistics operations, and underpin Defence capability.

Globally, increasingly diverse and open-market participation is revolutionising the space domain. This is facilitated by dramatic technology transformation and will spawn new disruptive industries and applications[2].

Key to all this is a sustainable space sector built on a foundation of excellence in science and technology.

Australia's space priorities are profoundly industry-focused. Australia aims to grow an internationally competitive space industry which will also build innovation capability and address strategic needs. However, there are many challenges. These include sustained declines in manufacturing output[i], STEM capability[ii], expenditure on R&D[iii], economic complexity[iv], skilled immigration[v], and growing geopolitical tensions.

The Australian Space Agency was established in 2018 with the objective to 'grow a globally respected Australian space industry'[3]. Its Civil Space Strategy identifies seven priority sectors for industry growth, with technical roadmaps outlining pathways to delivery. The Australian government has also identified space as one of six national manufacturing priority areas within a $1.3 billion Modern Manufacturing Initiative. Sovereign industry capability priorities necessary for the Australian Defence Force's tasks[4] are separately identified under the Australian Industry Capability plans[5].

These and other activities have led to significant new recent federal investment in space. These are welcome developments stimulating growth of the space industry sector. However, the space science research and innovation capabilities necessary to develop a sustainable national space ecosystem have not been similarly enabled.

This Plan takes a science-based approach. It focuses on the role and importance of space science by drawing on data and defensible evidence. The objectives of this Plan are to:

- Advance excellence in space science research, enabling leadership and international engagement on challenging programs of exploration and discovery, generating knowledge and stimulating innovation, and development of potentially transformative technologies.

---

[i] Value added to the Australian economy by manufacturing has decreased from 13.8% of GDP in 1990 to 5.6% in 2019, level with Ethiopia. Source: data.worldbank.org

[ii] Measured by PISA performance scores in reading, mathematics, and science. Source: data.oecd.org/australia

[iii] Gross domestic expenditure on R&D has fallen from 2.25% of GDP in 2008 (level with the OECD average), to 1.8% in 2017, compared with the OECD average of 2.4%. Source: data.oecd.org/australia

[iv] In the Harvard University Atlas of Economic Complexity, representing diversity and complexity of knowledge-based industries, Australia ranks 87 out of 133, worse than Albania, Guatamala and Uganda. Source: atlas.cid.harvard.edu

[v] See *Interim report of the inquiry into Australia's skilled migration program*, Joint Standing Committee on Migration, Canberra, March 2021

- Grow world-class fundamental and applied research to advance the capabilities and applications which underpin the use of space for societal benefit and national security.
- Train scientists and technologists across a range of domains enabling growth of the innovation sector.

Space science spans robotic and human space exploration; solar system planetary science; space weather science and mitigation of space weather events; remote sensing and Earth observation; space-based positioning, navigation and timing; satellite-enabled communication; and space life sciences. In every case, basic space science discoveries and innovations underpin space technologies, industries and applications.

In countries with mature space programs the space economy value chain usually comprises (a) public institutions which provide the scientific and technological foundations for space activity, (b) upstream sector providers (e.g. spacecraft hardware manufacturers and launch providers), (c) downstream sector providers (e.g. satellite operators and Earth observation, PNT, telecommunications applications), and (d) space-derived activities in other economic sectors[6]. Relationships between the key elements of the space sector are illustrated in Fig. 1. All sectors (a) to (c) are essential for sovereign capability.

High quality research and development is a core enabler of the space sector because it generates

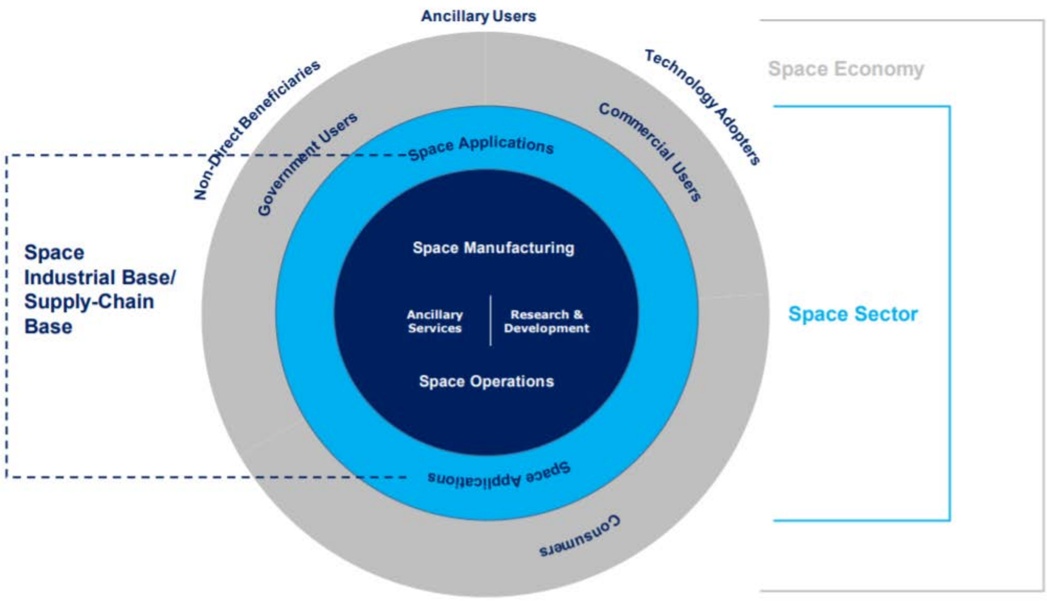


Fig. 1. Elements underpinning the space economy [Deloitte Access Economics, 2019]

new knowledge, products and processes, allowing organisations to use the inputs available to them more efficiently and to supply improved products or services to the space sector and broader community[7].

Australia has has extensive space heritage but in disparate domains that have been poorly connected and mostly not well-documented. In order to realise new opportunities Australia needs an innovative and agile space R&D sector. Institutional investors have yet to embrace this sector and government jurisdictions move slowly and are conservative. University research teams are skilled at achieving a lot with little, quickly, they collaborate with global leaders, and their performance is measured against international standards.

2.2 Australian Space Science

Strengths

Australian space science research is world-class in many areas. This is evidenced by the international standing of peer-reviewed Australian space and planetary science publications, and by Australia's ability to attract major international space conferences[vi] and contribute to international space science programs and missions.

In terms of the number and quality of publications, Australian space and planetary science is ranked 8th globally, comparable to Canada and well above China and Russia[vii] (Fig 2).

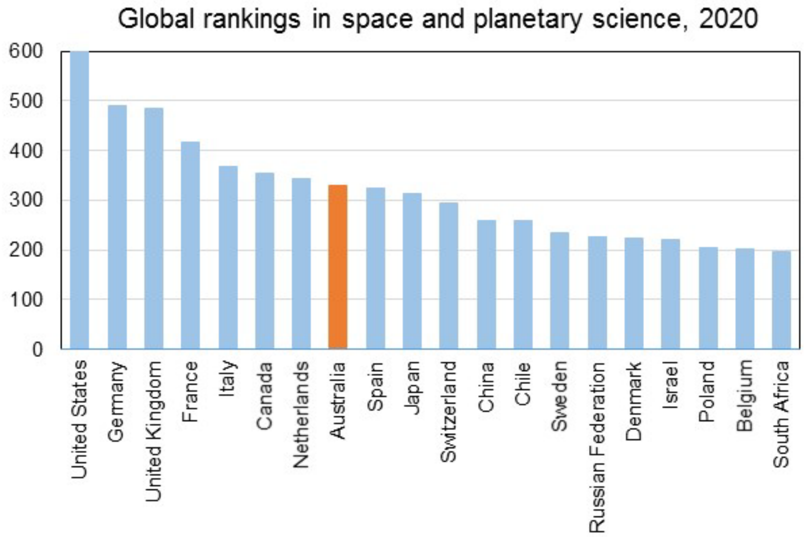


Fig. 2. Global rankings in space and planetary science, measured by H-index. Source: SCImago Journal and Country Rank, www.scimagojr.com

Australians have contributed to major international space missions since the Apollo era[viii], and continue to work at, and collaborate with, international space agencies, research groups and multinational consortia across all the key space science disciplines. These collaborations can leverage international expertise for national benefit.

Examples illustrating the scope of space science activities appear in Appendix C.

Weaknesses

Community consultation undertaken to inform this Plan (see accompanying volume) identified the following main barriers to growth of the space science sector. These findings complement a KPMG analysis of Australia's space sector[8].

1. Lack of a national priority for space science

Australian space science can make important contributions in support of national priorities, such as helping protect critical infrastructure, managing our environments, developing sovereign capability, and assisting transition of the workforce and economy to high value activities.

[vi] Recent space-related international conferences attracted to Australia include: International Astronautical Congress (IAC, Adelaide 2017); Committee on Space Research (COSPAR, Sydney 2020/21); Asia-Oceania Geosciences Society (AOGS, Melbourne 2022); Asia-Pacific Radio Science Conference (AP-RASC, Sydney 2022).
[vii] The OECD obtained the same ranking for Australian space science using a different methodology. Source: *Measuring the economic impact of the space sector*, OECD, October 2020
[viii] Stuart Ross Taylor (ANU) was NASA PI for lunar geochemistry, and Brian O'Brien (UWA) developed a lunar dust experiment which was deployed by Apollo 11-15.

However, there is no national priority enabling a sustainable space science R&D sector. Despite the strong focus on space industry and defence priorities, there is no recognition of underpinning space science in the National Science and Research Priorities, in the National Collaborative Research Infrastructure Strategy, or until recently, in the Field of Research classification[ix].

Funding for basic space science research has come principally for one-off projects from the Australian Research Council (ARC), and over 2016-2019 averaged $2.0 million p.a.[x] (one tenth the amount for astronomy research, and not counting major astronomy facilities funding[9]). Overall Australian government investment in space in 2019 was 0.003% of GDP[10], compared with Canada at 0.016% and South Korea at 0.03%. This is incompatible with Australia's national space ambitions and strategic priorities.

While groups such as Geoscience Australia (GA), CSIRO, and the Bureau of Meteorology (BoM), are excellent within their remits, they focus on applied or operational aspects and do not fund basic research, while the ASA and Defence are mostly concerned with mid-to-high-TRL developments able to be rapidly implemented. New federal investment in space activities (e.g. Moon to Mars initiative; SmartSat CRC) does not support basic space science and engineering research, or requires substantial commitments from industry partners. Competition between states and ad hoc grant schemes further confuse the picture. The result is an *ad hoc* funding environment, with new entities that have perceived or real overlapping remits with the ARC, but insufficient support to sustain the necessary basic research.

2. No national coordination and representation

Australia's space sector comprises many diverse elements across the defence, commercial and civil sectors but lacks an authoritative voice bringing them together with the research community to identify key goals and actions. The entire ecosystem should be working together to progress national space interests.

Space science R&D is an enabler for the space sector and much of this is based in universities. However, science is not mentioned in the Australian Civil Space Strategy 2019-2028. In this regard the ASA differs markedly from its overseas partner agencies, all of which identify science as a key strategic priority. This inhibits engagement with international space programs, impacting opportunities for Australian leadership of science missions, with flow-on effects on domestic industry capabilty.

3. No national strategy for a sustainable space sector

Australia has critical economic and strategic dependencies on space but no long-term plan to address knowledge and capability gaps. The key problem is lack of commitment to an ongoing, challenging national space program. This hinders long term decision-making by stakeholders, collaboration on major missions with international partners, translation of basic research to outcomes, development of sovereign capacity, and career pathways in the space workforce.

[ix] Until 2021, the Australian Field of Research Classifications grouped astronomy, astrophysics and space and planetary science disciplines together under a common heading. Dependent applications such as satellite design, satellite-based communication, navigation and remote sensing, are separate fields.

[x] Based on projects identified as primarily space science (e.g. in the Astronomical and Space Sciences FoR classification and clearly dealing with space science research), or identified as including space science (often in other FoR classifications). Does not include the SmartSat CRC.

4. A workforce skills and capacity gap

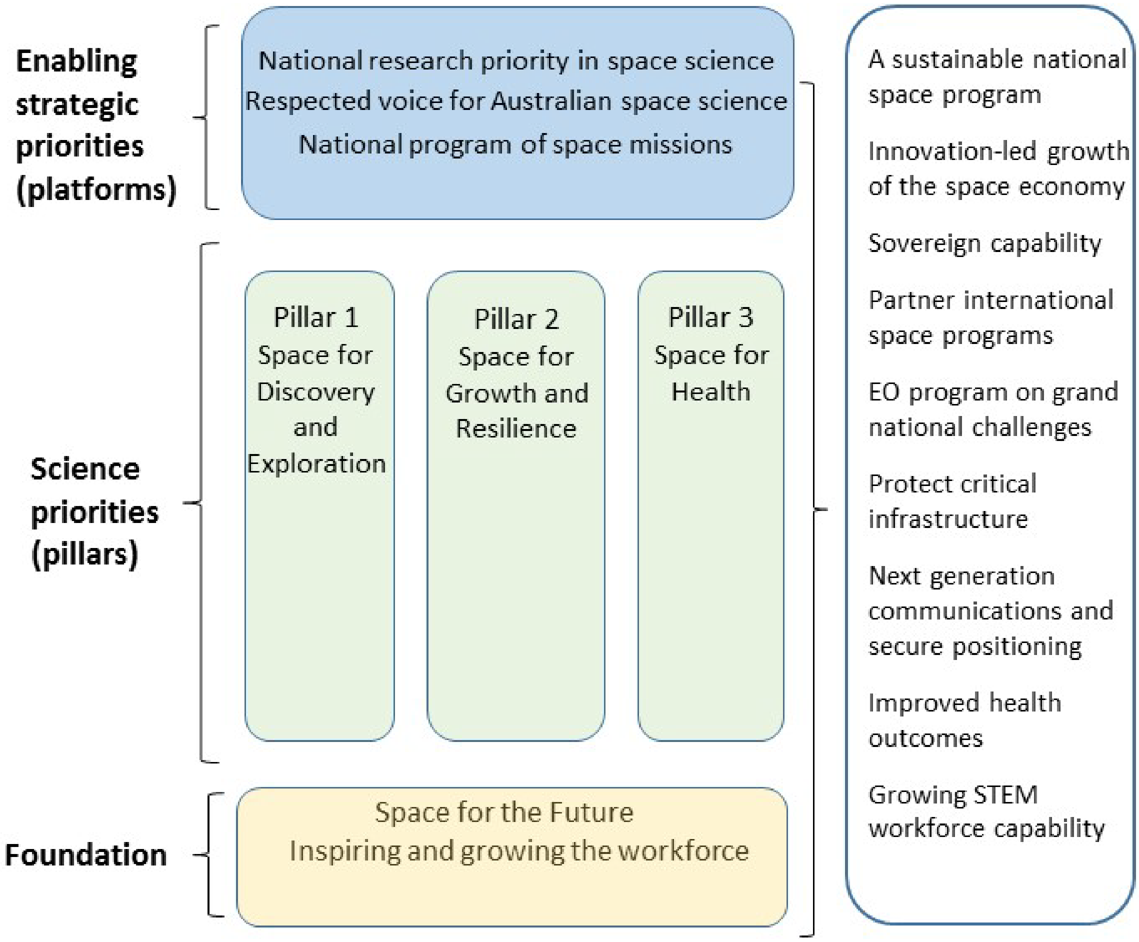
Australia's future depends on a highly skilled and diverse workforce.

However, a profound workforce skills gap is impacting the space industry[11] and Defence[12] sectors. In the downstream sector Australian companies and governments use highly skilled personnel to transform satellite-derived data to measurements and information. A much larger and rapidly increasing number of government, defence and private industries use information and services derived from these data, but would often be unaware of the satellite data pipeline. These sectors are growing rapidly and failure to meet the skilled workforce capacity represents a risk to economic, environmental and national security.

2.3 Strategy

The 2010-2019 Decadal Plan for Australian Space Science brought together Australia's space science community for the first time to identify strengths, aspirations and imperatives. These were important achievements, but much has changed since then.

The present Plan outlines a strategy to advance Australia's interests and priorities with a space science sector which drives innovation through mission-oriented capability goals. The strategy is outlined in Fig. 3.



Three overarching strategic priorities form the platforms which enable the main science priorities. These priorities focus on space science for discovery and exploration, and science-led innovation to benefit our economy, security and society. In reality, space science spans many sectors and disciplines, however this framework helps envision challenges and pathways to outcomes. Development of the workforce forms the underpinning foundation since without this Australia has no sustainable future space sector.

Enabling platforms

Three overarching strategic priorities form the enabling platforms necessary to deliver Plan outcomes.

1. A national research priority in space science

High quality research and development is a core enabler of the space sector value chain. Australian space science is world-standard but must be more effectively engaged in support of national space priorities. This will grow science capacity and foster development of the space industry sector and sovereign capability.

Recommendation

A national research priority in space science is needed that aligns with civil and defence sovereign industry capability requirements, and to encourage discovery, innovation and help build capacity for national benefit and international impact.

2. A respected voice for Australian space science

Australia lacks an authoritative voice which supports and harmonises engagement of Australia's space science expertise with the diverse elements of the domestic space sector and international science programs.

This role should include the following responsibilities.

(a) Vision and advocacy: developing the vision, goals and strategy for a coherent, sustainable space R&D system to underpin Australia's space priorities. This would require expansion of the ASA's current mandate and funding, for example as part of the review of its statutory basis to take place within four years of its establishment.
(b) International collaboration: providing a central point of contact between Australian scientists and international space agencies to collaborate on projects and missions, promoting discovery and technology transfer for national benefit.
(c) An ecosystem for cross-sector collaboration: facilitating interaction between academia, government, the private and industry sector, and end-users, to foster translation of research to practical outcomes.
(d) Capacity building: supporting development activities such as conferences, early career workshops and mentoring activities, and promoting equity, diversity and inclusion. Some of these activities are currently led by the Academy of Science's National Committee for Space and Radio Science, which is not resourced for such work.
(e) Education and outreach: fostering a coherent approach across national and state jurisdictions for space-related education and training.
(f) Sustainability and viability of the research sector: advocacy in support of a viable tertiary space R&D and training sector.

In line with international practice, the logical entity to perform this function is a Science Office, headed by a Lead Scientist, within our national space agency.

Recommendation

A respected voice is needed to represent and support engagement of Australia's space science expertise with diverse elements of the space sector, and provide a point of contact for collaboration on science missions with other agencies. This should take place through a Lead Scientist within the Australian Space Agency with responsibility for space science policy settings.

3. A national program of space missions

Australia needs a national strategy to build the critical mass necessary for sustainable growth of the space sector and sovereign capability. This requires commitment to national space program built around space missions. Our partner space agencies recognise this and have made science-focused space programs and missions core elements in their overall strategies[xi]. This is because science missions stimulate innovation[13] and bring interdisciplinary collaborators together to solve challenging problems, driving growth of the industy sector and promoting translation to outcomes.

Commitment to a national ongoing space program will provide confidence to overseas partners, funding agencies, industry and investors making long-term decisions.

The economic multiplier effects of such programs are well documented[14,15]. For example, the UK Space Agency investments in space science and innovation yield ₤3-4 in direct value to the space industry and additional spillover impacts of ₤6-12 for every ₤1 of public expenditure[16,17]. Spillover outcomes include job creation, revenue generation, productivity improvements, lives saved (or not lost), and lives improved[18,19]. Examples of mechanisms to facilitate development of spinoffs include NASA's highly successful Technology Transfer Program. The lag between investments and spillover impacts for space projects is around 3-5 years, a timeframe challenged by ad hoc and short duration funding schemes.

Space missions are inspirational. They grow the future space workforce by motivating students to pursue STEM and space-related careers, and by providing the high level training needed to embark on those careers. An exciting national space program will attract broad public appeal.

A national space program built around science missions will enable Australia to collaborate fully with overseas partners. Following international best practice, such a program should be led by the Australian Space Agency, with access to a specific competitive funding pool. This is compatible with the ASA's current remit to grow the space industry.

Recommendation

Commitment to and investment in an ongoing national space program, enabled by space missions which advance science, stimulate technical innovation, address national priorities, grow capability, and inspire citizens.

[xi] The Australian Space Agency has signed agreements with the space agencies of the UK, India, Italy, Germany, France, EU, USA, Canada, New Zealand, and the UAE. All of these operate science-focused space programs and all the agreements mention cooperation on space science and research.

3. Space Science Priorities

3.1 Space for Discovery and Exploration

'Failure within the mission itself is an option. Failure to progress as a nation is not.'
Omran Sharaf, Director of Emirates Mars Mission, Mohammed Bin Rashid Space Centre

Enabling innovation through science missions

Decades of international space activity have shown that the needs of bold science and exploration missions, rather than more operational space activity, drive innovation. Like Australia, our international partners are also interested in growing their innovation sectors and realising economic and strategic benefits. They recognise the importance of a challenging space program in this regard. For example, Canada's Space Strategy aims at "growing the economy … and ensuring that the benefits of a more innovative society are shared among all Canadians"[20]. Their Strategy is called *Exploration, Imagination, Innovation* and it focuses on science and research excellence, delivered through space science and exploration missions; Earth observation, climate change science and communications missions; and using space activity to simulate STEM engagement.

Science-focused missions, involving concepts and advances from research groups incentivised by international collaboration and spin-off opportunities, must be prominent in Australia's efforts to grow the industry.

Our vision for 2030 is to see Australia become an equal partner in the global community of spacefaring nations by leading our own science missions, with Australian-led science teams, and Australian-built payloads and spacecraft systems. These missions will propel breakthrough science and technologies. Australian hardware, software and scientific expertise will then contribute to the most significant international space missions. We will create a world-class workforce of scientists and engineers, trained on missions, to feed a burgeoning industry and research sector, and act as ambassadors for our nation as we engage with other agencies.

The development pipeline to realise this vision is based on:

(a) significant numbers of highly innovative low cost science-driven nano- and microsatellite missions which develop new technologies and grow collaborations and capability;

(b) smaller numbers of high value small satellite missions focused on priority topics, growing our science horizons, industry capacity and practical applications; and

(c) flagship missions addressing grand national challenges and delivering sovereign capability.

Key opportunities for the next decade

The playing field for Australian space science has been redefined by enhanced access to space, strategic partnerships with international space agencies, and technological advances enabling small satellites to deliver big science.

Artemis provides an example. It is NASA's major program for human Lunar exploration, providing an R&D stepping stone to future crewed missions to Mars. NASA is planning 72 missions to the Moon by 2030[21]. Many of the science and technology payloads will be delivered by private contractors. The continual flow of large payloads to Lunar orbit and the Lunar surface translates to multiple rideshare opportunities per year to cislunar space for secondary payloads over the next decade. There will be further opportunities for deep space missions.

Artemis 1 will fly thirteen low cost CubeSat missions as secondary payloads. These will conduct science and technology research. This represents a radically different approach to science delivery, incorporating highly integrated miniaturised payloads into compact, lightweight, low cost spacecraft. Australia can share the opportunities Artemis provides. There are further opportunities through, for example, NASA's SIMPLEx (Small Innovative Missions for Planetary Exploration) program.

Box: Nanosatellite mission case studies

Lunar Ice Cube

Lunar Ice Cube is a small (6U) orbiter mission to prospect, locate, and estimate the amount and composition of water ice deposits on the Moon for future exploitation by robots or humans. It will fly as secondary payload on the first Artemis mission. Lunar Ice Cube is led by Morehead State University, and the flight software is being developed by Vermont Technical College. Morehead State is a small regional US liberal arts university, similar in global rankings to Torrens University in Adelaide. Vermont Tech is one quarter the size of Morehead but has already developed its own CubeSat which operated for two years. It tested a robotic navigation system which can guide an autonomous CubeSat Lunar Lander. Both Morehead and Vermont began their CubeSat programs through NASA's CubeSat Launch Initiative, which provides opportunities for small satellite payloads built by schools and universities. With support from the State of Kentucky, Morehead State invested in spacecraft engineering as a new strategic area. Now they're leading an Artemis mission, and building spacecraft which can advance human exploration of the Moon. Australia has world class university science and engineering departments which could also lead world class missions.

Canadian CubeSat Project

The Canadian CubeSat Project, announced in April 2017, provides grants of up to $250k to college and university research leaders to engage students in a real space mission, building a CubeSat to be launched from the International Space Station. Funded by the Canadian Space Agency (CSA), 15 projects were competitively selected involving 37 organisations and collaborations with universities in Europe, Australia and the USA. The projects involve researchers and students in all aspects of satellite design, fabrication, licensing, operation and data analysis (launches are organised by the CSA). The projects are science-driven and include space weather studies, Earth observation, technology development, precision agriculture, indigenous culture, and quantum communications. CSA experts provide support to optimise mission success. This program increases Canada's space capacity and capability, advances Canadian space science and technology, and promotes STEM engagement, for a total cost of less than $3 million over 4 years.

But we can also be smarter.

Artemis and SIMPLEx missions are competitively selected for that one opportunity, meaning that some spacecraft systems and payloads are reinvented by multiple teams. Average cost per Atermis CubeSat mission is around US$10-15M. Australia can improve on this model. There is a place for large flagship Australian missions but the Artemis 1 CubeSats suggest an alternative: an agile approach with fast turnaround missions and targeted science goals, small spacecraft with advanced highly integrated systems, and small teams enabling rapid innovation. The technology exemplified by these small spacecraft is eminently achievable by Australia.

We envisage a program comprising multiple missions leveraging the space infrastructure being built by international partners. A mission R&D program of AU$40M over 4 years will build and validate a range of science payloads and spacecraft systems enabling modular mission design. This would be followed by a 4 year $80M mission program which would see multiple Australian spacecraft exploring the solar system by 2030. These programs would deliver a unique, agile, sovereign space capability, and preferred partnership status for international space collaborations. The programs would stimulate innovation driving a thriving space science and advanced manufacturing and supply chain sector. They would inspire a generation of young Australians in STEM, and directly engage student scientists and engineers forming Australia's future space workforce.

Key science questions for the next decade

Here we identify key solar system science 'discovery' questions we can address. These build on Australian research strengths, international collaborations which help develop domestic capacity, and global research priorities. Some of these are discussed further later, as are other Earth-focused missions.

1. Formation and evolution of the solar system

What were the initial processes of solar system formation and the nature of the interstellar matter that was incorporated? We understand much of how our Earth works. But how Earth and other terrestrial planets formed, and how and where the gas giant planets formed, is still a mystery. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? The Moon, Mars, asteroids (from which meteorites come) and comets, contain a unique record of solar system formation. Australia is a world leader in the analysis and characterisation of extra-terrestrial materials, whether it be samples brought back by JAXA, NASA, and CNSA missions, or meteorites. We can build on that, leading our own missions to these bodies.

2. Habitable worlds

How, why and where did life evolve in the solar system? Leveraging key Australian strengths in astrobiology and analogue site studies, there is an opportunity to develop Australian payloads around key science questions and knowledge gaps. Western Australia has the earliest and rarest evidence of life on Earth 3.8 billion years ago and an ancient hot spring environment, both of which attract space agencies and researchers from around the world. Key questions focus on the primordial sources of organic matter, whether Mars or Venus hosted ancient environments conducive to early life, and whether there are modern habitats elsewhere in the solar system with necessary conditions to sustain life. This is also an area where advanced Earth observation techniques can be further developed for detection and measurement of key variables.

3. How the Sun interacts with Earth

How does energy transfer from the Sun through interplanetary and near-Earth space, driving space weather on Earth? The solar wind couples most directly to Earth's atmosphere at high latitudes, generating a wide variety of disturbances. How these reach low and equatorial latitudes is not well understood. This has important consequences for satellite-based position navigation and timing systems, and operation of the JORN surveillance radar, for example. A different set of physical interactions generate "killer electrons" which can damage spacecraft, affect atmospheric chemistry and ozone concentrations, and ground level temperatures at polar latitudes during large magnetic storms. An Australian space weather constellation program could provide critical data, addressing fundamental science questions while helping protect key infrastructure.

4. Return to the Moon

There is so much we still do not know about Earth's nearest neighbour. When did it form? What can its ancient surface, and record of impacts, tell us about the impact history of the solar system? The Artemis program allows Australia to participate in a new era for Lunar science. The NASA Commercial Lunar Payload Services (CLPS) program offers an unprecedented opportunity, with low cost options to access the surface with lander or rover payloads, or via delivery of remote sensing platforms to orbit. Working closely with NASA on science projects as part of Artemis, Australian science teams can operate hardware on the surface or in orbit to address key knowledge gaps[22]. We should develop nanosatellites to explore and deliver services from Lunar orbit, and Lunar science and exploration payloads.

5. Enabling human exploration: in situ resource utilisation

Australia can partner with other agencies in characterising the composition of the Lunar and Martian surfaces, their material properties, and dust environments – all key to determining the economic and ISRU potential of the Moon and Mars, and constraining hazards to human health. This area is the focus of a co-ordinated NASA program – the Solar System Exploration Research Virtual Institute (SSERVI), which supports domestic US science teams and collaborations with international partners on missions on the origin and evolution of the inner solar system. Australia is a key SSERVI partner, with 12 Australian institutions[23] participating in 19 international space missions. Relationships built within NASA SSERVI on projects to determine volatile content and distribution for ISRU, our track record in sample analysis, and Federal support for Artemis, potentially make us a preferred national partner with NASA in this area.

6. New avenues for radio astronomy

Radio astronomy is constrained by interference from artificial sources, and distortions due to Earth's ionosphere at frequencies below 30 MHz. The domain below this frequency is almost unexplored. The processes that occur in the largest physical scales and the lowest energy levels, including the cosmological Dark Ages, the epoch of reionization, solar and planetary bursts, and exoplanet RF emissions, are practically solely detectable by a low frequency interferometer array. An observatory on the Moon capable of such observations would be extremely challenging to realise. However, a radio telescope comprising a network of optically linked CubeSats in RFI-free Lissajous orbits around the Earth-Moon L2 Lagrange is realistically achievable[24]. This could be developed iteratively and would provide tremendous opportunties for breakthrough science, industry and spinoffs, and high level training. Do we dare to be bold?

Recommendation

Establish a program of small space missions to advance knowledge and discovery, foster and leverage international collaboration, accelerate development of new technologies and applications, skilled workforce and help grow sovereign capability. This should be the responsibility of the Australian Space Agency, with NCRIS or similar support.

3.2 Space for Growth and Resilience

'Sometime in the future, science will be able to create realities that we can't even begin to imagine.'
Robert Lanza

Space science and technologies are profoundly dual use in nature. To date Australia's critical economic and strategic dependencies on space have largely relied on global supply chains and strategic alliances. The ADF is now tasked with developing Space Situational Awareness (SSA) capability and sovereign space-based geointelligence, surveillance, communications and control networks[25]. However, transformational change is catalysing new opportunities and risks.

Here we outline opportunities for Australian space science to advance national interests, by exploiting competitive advantages including R&D strengths.

Understanding and managing our changing environments

Significance

Earth observation (EO) data transformed into scientifically valid measurements and information are essential for managing our environments and resources, forecasting weather, understanding and responding to climate change, responding to natural disasters, and urban planning. Satellites furnish the bulk of EO observations: for example, comprising around 95% of the observations used by the Bureau of Meteorology in the weather, hydrological and ocean models to deliver its services. The economic benefit to Australia of space-based EO data in 2020 is estimated at $2.5 billion[26].

All satellite data used by Australia comes from foreign sources. All jurisdictions, from government to defence to commercial, require long-term continuity and security of supply of EO data and derived products. Australia is an active member of the World Meteorological Organisation (WMO), which under Resolution 40 provides free and open exchange of satellite data to members. However, there is no guarantee all necessary data sources will always be freely available, optimal, or meet specific and evolving needs. This imposes a sovereign risk, alongside reputational risk if Australia is regarded as an unequal contributor to the global EO community. Defence project DEF799 recognises some of these risks by seeking to provide 'direct and timely access to commercial imagery satellites … [and] the possible acquisition of a sovereign GEOINT space surveillance system'.

Australia's EO data requirements will increase in the face of increasing environmental, commercial and geopolitical stresses.

Our competitive advantages

Australia's important advantages include the following.

- Respected membership of the WMO, the international Group on Earth Observations (GEO) and the Committee on Earth Observation Satellites (CEOS), and an authoritative voice on space-based Earth science research and applications. Partly this arises from Australia's expertise in development of innovative EO applications, platforms and products (e.g. the Open Data Cube platform supporting Digital Earth Australia and other countries via the CEOS Open Data Cube).
- Strong collaborative partnerships with international agencies such as NASA, USGS, ESA, DLR, JAXA, Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), Chinese Academy of Sciences.
- World-class Earth observation research centres (e.g. Earthbyte group hosted by the University of Sydney; CSIRO's Centre for Earth Observation; University of Queensland's Remote Sensing

Research Centre and associated research-to-operations programs in governments and industry; ANU's Centre for Water and Landscape Dynamics; BoM's Earth system modelling; FrontierSI).

- National infrastructure facilities including AuScope (services, data and analytics for geoscience research), TERN (collecting and providing terrestrial ecosystem research data), IMOS (collecting and providing oceanic ecosystem research data).
- Australia's large and diverse territory, extensive infrastructure and scientific and technical expertise, providing unique opportunities for ground truthing of satellite observations[xii].

Opportunities and enablers

Monitoring, understanding and effectively managing our environments, resources and security in the climate change era poses grand national challenges. Addressing these requires: (a) ongoing access to a broad range of international data sources and platforms, through active participation in the global observing system; (b) appropriate sovereign capability to mitigate supply risks in the evolving commercial and geopolitical landscape; and (c) enhanced science, observations, analysis and modelling capability. For example, reducing the detection time of bushfires by 30 min can result in an economic benefit of around $3 billion over 30 years, rising to more than $8 billion if all fires are detected within 30 min[27].

Ultimatley, meeting Australia's future EO needs requires an ongoing national science-focused civil space program, aligned with ASA and GA priorities and roadmaps, and potentially dual use programs. Such a space program would support sovereign data capability, keep the Australian EO science community at the leading edge, grow EO expertise and capability, engage local industry, and help grow global market share in niche areas where we could be world leading. Australia's expertise in delivering decision ready, scientifically and legally valid information from EO data analytics, can be exploited further to allow Australians to lead domains transitioning scientific research to commercial and government applications.

A useful analogy for such a program is the NASA Earth Venture Program (see Box). This consists of innovative, low cost, competitively selected science-driven missions which produce new research and applications that enhance understanding of the Earth system, improving the prediction of future changes, and building a skilled workforce with technical capacity.

A compelling economic argument for a sovereign, continuous launch small satellite EO program, costing around $36 million per year from 2203-2040, has been produced by Deloitte for GA.

Here we identify stepping stones to realising a national EO program.

1. Nanosatellites and constellations in LEO to improve understanding of a range of topics, such as atmospheric temperature and moisture dynamics, wind and wave directions, ground-level water volumes and quality, evapotranspiration and agricultural water consumption, crop development and impact of pests and diseases, development of bushfire fuel loads and fire occurrence, impacts of infrastructure on urban microclimates, identification of potential mineral deposits. The emphasis is on 'pre-operational', low-TRL but challenging science missions by universities and SMEs to stimulate disruptive innovation by developing new sensors, smart payloads including on-board processing, reconfigurable low-cost platforms, and novel data analytics. Relevant technologies include optical imaging (visible, thermal and reflected infrared, hyperspectral), radio (real and synthetic aperture radar, radio occultation, microwave hyperspectral imaging), and high precision gravity measurements with laser range finding. Cross-sector collaboration will be important; for example, a University of Melbourne team is leading

[xii] Such activities are currently conducted, for example, by CSIRO

development of a low noise infrared telescope for a 12U CubeSat astronomy mission called Skyhopper.
2. Same as above but maturing to small (some 10's kg) high value satellites with enhanced capabilities, engaging and advancing industry capability and supporting the growth needed for delivery of strategic requirements such as Defence's DEF799 program, and help industry realise new market opportunities. Examples of EO missions of this calibre include the Canadian Space Agency's RADARSAT constellation and WildFireSat, and the Argentina Space Agency's SABIA-Mar marine science mission.
3. A national quality assurance capability for satellite Earth observation instruments, data and derived measurements, products and services. This would use ground/water-based quality assurance infrastructure and a continuous series of Australian cross-calibration radiometer satellites to assure scientific veracity and data interoperability between various EO datasets. Australia would be positioned as an international leader and global resource for remote sensing calibration and validation advancements, also helping assure the long-term supply of critical EO data streams and enabling new science applications. A scoping study to inform the ASA's Earth Observation from Space Technology Roadmap has detailed such a calibration and validation program[28] and is strongly supported by the US Geological Survey (responsible for the Landsat program). This would also complement other programs such as ESA's TRUTHS mission.
4. Complex, high value payloads on the International Space Station and large geostationary platforms, in conjunction with other space agencies, to provide high cadence weather and environmental data specifically for Australian applications. One example is NASA's GeoCarb instrument to monitor CO_2 sinks and sources and plant health and vegetation stress through the Americas.
5. Sophisticated processing algorithms and methods to ingest and break down vast and growing volumes of EO data into smaller more dedicated chunks for less technical end users. This can open new markets for products and services. The Australian Space Data Analysis Facility is already providing some of this capability.

Box: NASA CYGNSS Mission

The Cyclone Global Navigation Satellite System (CYGNSS) is an element in NASA's Earth Venture program. It comprises a constellation of eight 29 kg satellites in LEO measuring ocean surface winds using GNSS reflectometry – direct and reflected signals from GPS satellites – to determine location and surface roughness. The project is led by the Southwest Research Institute at the University of Michigan and has been highly successful, with mission life extended from an initial two to nearly six years. Outcomes to date include soil moisture measurements for eastern Africa, used by the World Health Organisation; better location of storm centres and movement; imaging coastal flooding after hurricane landfall; and establishing river flow rates and widths following extreme weather events. Similar GNSS reflectometry receivers will now be deployed by NASA on Air New Zealand aircraft to collect environmental science data over New Zealand.

The Australian Centre for Space Engineering (ACSER) at the University of New South Wales has built and flown CubeSats and developed a GNSS reflectometry receiver payload with CubeSat form factor. These can also be modified to provide radio occultation data, which can significantly improve weather forecasting. Australia could fully develop a sovereign CYGNSS program, and, given that the UNSW receivers are also being deployed experimentally on aircraft and UAVs at low to very high altitudes, fly such receivers on operational Australian aircraft missions.

Recommendation

Australia should develop an ongoing Earth observation satellite program to mitigate data supply risk, address grand national challenges, grow capacity, and contribute to global programs. As part of this Australia should lead an international effort on global instrument calibration and validation. This program should be led by the Australian Space Agency.

Next generation global communications

Satellite communications and dependent services (EO, ground stations, direct to home TV) accounted for 76% of Australian space industry revenue in 2018[29]. Currently all satellite services are enabled through radio communication. However, spectrum space is limited and increasingly congested, already impacting some EO missions. Furthermore, services delivered via satellites in geostationary orbit experience are too slow for many applications[xiii]. Seamless global, high capacity, low latency communications can transform economies and society, enabling 'big data' and machine-to-machine IoT.

The dual use nature of space means that needs and developments overlap the defence, civil and commercial sectors.

Future high capacity global communications will likely be facilitated by resource sharing across multiple satellite systems in GEO and networked megaconstellations in LEO; smart and adaptive on-board and on-ground processing, and advances in hybrid RF and optical communications technology.

New science and technology are required to exploit opportunities. Considerable heritage and expertise exists in government agencies (e.g. CSIRO, DST Group), university-based groups and entities such as the Institute for Telecommunications Research, the SmartSat CRC, industry groups and SMEs. Pathways for development of technologies offering greatest opportunity for Australia are outlined in the ASA's Communications Technologies and Services technical roadmap 2021-2030. However, research topics and specific actions to achieve outcomes including the necessary funding commitments are not identified.

Research needs and breakthrough opportunities

Areas of research need and opportunity, complementing aims of the Roadmap, include the following.

- Mitigation of optical channel degradation due to atmospheric effects (e.g. adaptive optics, diversity, channel coding)
- Advanced signal processing and waveform standards for interference mitigation of RF channels
- Advanced satellite on-board electronics, including development of millimetre wave devices and circuits, allowing higher throughput communications payloads
- Advanced antenna research and design to improve performance and flexibility, e.g. contoured and adaptive beamshaping, multifeed applications, CubeSat antennas

---

[xiii] The communications latency for satellites in GEO, such as the NBN-Co Skymuster satellites, is limited by the speed of light to 600 ms. LEO satellites, such as SpaceX Starlink system offer latency around 20 ms and data rates up to 10 times higher than Skymuster.

- High speed hybrid RF-optical, and free space laser optical communication to significantly improve bandwidth, data capacity and security (see below)

Quantum technologies offer breakthrough improvements in secure communications but corresponding risks to public-key cryptography. A recent report[30] by the former Chief Defence Scientist and an eminent expert working group proposed five recommendations to boost Australia's quantum information science capabilities and strengthen national security. One of these is to establish a mathematical and theoretical sciences research institute to act as a bridge between the academic and defence communities. This would provide a nexus for research and foster a talent pipeline. There is much merit in this concept, which could be applied more broadly to encompass a range of space science topics where academic and civilian expertise can inform strategic programs. Notable examples of such an approach are the Applied Physics Laboratory at Johns Hopkins University, and the Aerospace Corporation.

The report also identifies specific scientific applications of potential relevance to Defence, including investigation of **coherent optical links** between satellites for extended quantum sensing (e.g. between NASA's GRACE-FO satellites to increase the precision of gravity measurements), and **distributed coherent optical imaging** between satellites to improve imaging resolution (i.e. aperture synthesis). Such concepts open new avenues for scientific and technical innovation. For example, constellations of low cost microsatellites in LEO interconnected by optical links, can provide a range of services such as regional or global communications or EO, while similar networks in cislunar orbit can provide scientific data and support Artemis and planetary missions[31].

An important goal would be demonstration of **in-orbit optical communication** between a small constellation of nanosatellites and to the ground, paving the way for more ambitious quantum capable assets including networked swarms in LEO, and eventually in cislunar orbit. Such a project should be achievable at modest cost using a modular platform approach.

Some of these activities are currently supported under the ASA's Moon to Mars Initiative. Achieving a sustainable program of activity requires ongoing support for both fundamental research activities and applied R&D. Mechanisms fostering cross-sector academia-government-industry collaboration are vital. Cross-disciplinary science collaboration should also engage the astronomy community, which has expertise in large and complex data handling and processing capabilities, and correction for atmospheric distortions of optical signal paths.

Resilient Position, Navigation and Timing (PNT) services

Significance

PNT services derived from global navigation satellite systems (GNSS, e.g. GPS) underpin commerce and business activity, personal user applications, new technologies including precision agriculture and IoT, and mission- and safety-critical applications such as autonomous machines and vehicles, and much defence capability.

Many science applications are also enabled by PNT services. These include meteorology, geodesy, geodynamics, geophysics, space physics, oceanography, land surface and ecosystem studies. These embrace domains such as environmental and climate change monitoring, resources exploitation, and space domain awareness. Techniques include direct and reflected GNSS signals, differential measurements, phase measurements, and radio occultation measurements.

Australia's reliance on accurate, available and reliable PNT information will continue to expand, amplifying concerns about vulnerabilities and risks, for example to cyber attacks, jamming and spoofing.

Building resilience

Some of the measures necessary to build resilience in our PNT infrastructure will be organisational but many will involve the convergence of traditional PNT science and technology with non-traditional and emerging developments. These include developing, testing and implementing back-up or alternative GNSS-PNT technologies such as multi-sensor systems, and development of classical and quantum technologies to provide GNSS-independent PNT capability. The DST STaR Shot program 'Quantum assured PNT' has this focus.

Such efforts will depend on cross-sector cooperation and collaboration to ensure interoperability of technologies, translation of research to implementable outcomes, and measures to grow workforce skills and capacity. Opportunities to commercialise resilient PNT products and services may also emerge.

Science underpins all PNT technologies and applications. The deployment of SouthPAN (formerly SBAS) as part of Australia's national positioning infrastructure will provide decimetre positioning precision enabling new applications and improved productivity. However, there are important limitations which need to be better understood and mitigated through basic and applied research. Future PNT may involve signals of opportunity from a combination of services delivered by commercial operators of satellite constellations, 5G/6G, and internet-enabled ground technology. Future developments will also focus on next generation GNSS real-time absolute navigation at sub-centimetre level (e.g. using real-time kinematic, precise point positioning, and smart post-processing technologies).

It is important that Australia builds upon its PNT capability as technology continues to develop. This requires a focus on research topics offering particular opportunity, including the following:

- aspects of metrology (e.g. on board and ground clocks to improve precise time synchronisation and real-time kinematic applications)
- advanced signal processing (e.g. to reduce interference and jamming impacts)
- precise orbit determination, including space weather effects
- handling difficult signal propagation conditions
- enhanced, real time tropospheric and ionospheric corrections (to improve positioning and provide vital data for weather forecasting and ionospheric tomography)
- antenna science (e.g. phased array and reconfigurable reflectarray antennas)
- smartphone-based positioning
- multi-constellation aspects (e.g. multi-frequency precise point positioning offering centimetre positioning accuracy, enhanced robustness, and near real-time convergence times)
- multisensory integration (e.g. GNSS, communications, camera, inertial).

Recommendation

Australia should commit to an integrated program to advance basic and applied research on transformative technologies in secure, high bandwidth RF and optical communications technologies including across satellite networks, advanced on-board processing, and next generation secure positioning, navigation and timing capabilities. This should include technology demonstrator satellite missions and associated ground infrastructure.

Assuring our critical infrastructure and sustainable use of space

Significance

All spacecraft and space-reliant services and much critical infrastructure are at risk from space weather and space debris.

Solar eruptions trigger magnetic storms and space weather events which can damage satellites and affect their orbits, degrade radio communications links, over-the-horizon radar operations and GNSS services, impact aviation, and damage long pipelines and electricity distribution grids. Space weather monitoring and forecasting is therefore critical to maintaining the integrity of space-related services in Australia[32]. The United Nations regards space weather as a global high impact threat because of the interconnectedness of economies[33].

The benchmark extreme space weather event is the 'Carrington Event', which occurred in 1859. Such an event today would cause catastrophic failure across a range of critical sectors. Estimates of its probability range from 0.5-12% within the next 10 years[34]. However, collaborative work by BoM's Space Weather Service, GA, academia, and transmission and distribution network service providers, has highlighted risks to Australian and New Zealand power grids from more moderate scale events which may occur many times per year during the active phase of the solar cycle.

Current capability provides around 1 hr warning of major space weather events, with general indications of potential events over the preceding day or two.

The space environment is becoming an increasingly commercial, congested, and contested. Around a million pieces of space debris over 1cm in size currently orbit Earth, but only about 22,000 objects are tracked. The number of satellites in orbit will grow by a factor of 10 within a decade. The concepts of space situational awareness (SSA; detecting and tracking objects), space domain awareness (SDA; knowing about factors that affect the use of space), and space traffic management (STM; ensuring safe use of space) span military and, increasingly, civil and commercial domains. Legacy approaches to SSA/STM/STA are challenged by the vast growth in the number of space objects and in-orbit capabilities, and the need to incorporate physics-based models including space weather effects.

The resulting increasing risk of collisions jeopardises all space assets and threatens the sustainable use of space[35].

Australia has an international commitment to action on space debris management through membership of the UN's Committee on Peaceful Uses of Outer Space, and the joint agreement from the G7 Leaders' Summit in June 2021 'to the safe and sustainable use of space to support humanity's ambition now and in the future'[36].

National needs and assets

Australia requires a tightly integrated and sovereign space weather and SSA capability across the defence, civil, and commercial space sectors. However, basic space weather research has not been identified as a priority area by the ASA, CSIRO, or the ADF, and is mostly undertaken by insecurely funded university groups. BoM's Space Weather Service is responsible for operational space weather forecasting (see box) but not the underpinning research.

Australia's territorial interests span 1/8th of the globe, from Antarctica to near the equator and over strategically important time zones. Australian assets across this region include world-class monolithic and distributed sensors spanning optical, passive and active RF, radar, infrared, laser ranging, and spectrum monitoring. These are operated more or less independently by various organisations including the ADF, BoM, CSIRO and the MWA/SKA consortium, industry groups, and university groups. Under Project JP9360 the ADF aims to develop a multi-technology, multi-layered sensor network to collect sovereign controlled SSA data through already mature technology with industry partnerships. This may incorporate space weather and in situ observations in time, but there is no sense that the ADF will pursue basic breakthrough research or be tasked with responsibility for protecting critical infrastructure. Instead, Australia's core SDA product needs will be sourced from the US.

We can and should do better than this. Several Australian university groups are at the forefront of international research in solar and near-Earth space physics. By exploiting our geographical extent and growing our space science and SSA capability Australia can become a medium to major player in managing the global commons of space, while building resilience for space-dependent services, growing sovereign SDA and STM capability, exploring new commercial opportunities, and supporting NASA's deep space and Lunar SDA programs.

Key science questions and opportunities

Despite intense international research efforts we are still a long way from high fidelity prediction of severe, or more frequent less severe, space weather. However, there is a window of opportunity for Australia to advance globally important space weather science and operational outcomes. Here we identify the main topics Australia can lead.

Characterising extreme space weather. Our Sun is much less active than other Sun-like stars[37]. We need to understand if this is a permanent condition or if extreme solar activity varies over longer time spans than human records. The study of space weather in other planetary systems can show how, over time, stellar winds interact with magnetospheres and atmospheres, and implications for planetary habitability.

Predicting solar activity. Can helioseismology (imaging of the far side of the Sun) and physics-based modelling and data-driven simulation of solar flares, mass ejections and the magnetic field, provide transformative improvements in the prediction of solar activity? Australia has significant expertise in these areas.

Tracking space weather triggers from the Sun to Earth. Critical to improved space weather prediction is the timing, evolution and properties of shocks, mass ejections and electromagnetic emissions in the solar wind. Current state-of-the-art predicts arrival times within 12 ± 12 hr. New observations from NASA spacecraft and the MWA/SKA radio telescopes, combined with simulation models, suggest this uncertainty could be improved to 2 ± 2 hr or better.

Space weather effects in the ionosphere. The ionosphere is a highly dynamic region driven from above by space weather and from beneath by the neutral atmosphere. By combining our expertise in ionospheric physics, extensive sensor networks, international collaborations, and operational tools used by the BoM Space Weather Service, Australia is exquisitely placed to improve understanding of space weather effects in the mid- to low latitude ionosphere. These regions are not well understood but affect GNSS systems including SouthPAN, HF radio and defence surveillance radars, low frequency radio astronomy, and synthetic aperture radar measurements by EO satellites.

Impacts on LEO satellites. LEO satellites experience high radiation levels, variable hot and cold plasma populations, magnetic perturbations, electric currents, and drag from neutral particles. All these systems are driven by space weather. Current orbit determination algorithms use statistical optimisation techniques but more sophisticated physics-based models, taking into account space weather effects, would provide improved solutions. Australia can make important contributions through innovative laboratory and in-orbit experiments to inform improved modelling and suggest mitigation strategies. Such capability would also complement and enhance Defence's SSA program, and allow Australia to offer services into the new commercial SDA market.

Predicting effects on power grids and pipelines. Sophisticated mathematical models of ionospheric and geomagnetic-induced ground currents are required to predict space weather effects on long conductors. This must be done locally since ground structure varies regionally. Australia's expertise in space physics, geophysics, power line network modelling, and industry support, position us as an international leader in this regard. With further work, reliable models can be developed to predict the impact of geomagnetic storms on power networks and corrosion of long pipelines across Australia. This would be an important step in protecting our critical infrastructure.

Space weather and SDA for cislunar, Lunar and deep space missions. Australia is partnering with NASA for the Artemis Moon to Mars program. Long duration crewed space missions require advanced capability in space weather prediction and deep space surveillance. Blue-sky research built upon existing capabilities should be exploited to secure Australia as a preferred partner in lunar and deep space SSA, STM, SDA and space weather.

Enablers

Research program. Realising the above opportunities requires a collaborative program of fundamental and applied science on space-environment interactions. This would build upon existing capabilities spanning sensor networks, data processing and analytics, physics modelling and machine learning, and harness collaborations with trusted international partners. A mechanism to achieve this is through establishment of a research Institute or Centre tasked with developing breakthrough space weather science and collaborations with industry and government partners, to mitigate risks to critical infrastructure, support Australia's strategic goals, and promote translation to outcomes.

Expanded ground-based and in-orbit sensor network. A comprehensive range of ground-based space weather and SSA sensors exists across mainland Australia. The manner in which solar wind disturbances arriving at high latitudes generate space weather effects at low and equatorial latitudes is not well understood. Furthermore, LEO altitudes are critically undersampled from the space weather perspective. Therefore the research program requires:

(a) Augmentation of the existing suite of ground-based sensors (e.g. HF radars, magnetometers, GNSS receivers) to sample latitudes poleward and equatorward of Australia. These would also complement and enhance operational aspects of JORN.

(b) a regular cadence of space science and SSA spacecraft missions to generate benchmark quality truth data to verify and validate ground-based sensors, data processing, modelling and simulation tools. These missions would provide a low-risk pathway for the development of operational space-based space surveillance and space weather payloads, and support strategic alliances. Australian groups have the capability to develop CubeSat platforms with a variety of space weather and combined meteorology (GNSS radio occultation) payloads, which could also form elements of global multinational constellations.

Such infrastructure will provide globally significant space weather and SSA capability, but to ensure viability should be funded as a national facility.

Virtual observatory and analysis centre. The complete space weather and SDA picture only emerges when many diverse sources of data are intelligently combined, analysed, and acted upon. This requires a single, coordinated and curated virtual observatory and analysis centre, providing access to a multitude of Australian and international ground- and space based datasets, and data assimilation, visualisation and machine learning analysis tools. This will connect the capabilities of the Australian space weather and SSA community, enabling rapid developments that lead toward operational capability. Its aim is to support new breakthrough research outcomes, and ADF's SSA program via suitable protocols. **To remove financial and technical barriers this should be a well-funded national facility.** It could operate alongside or as part of the Australian Space Data Analysis Facility.

Recommendation

A national program focusing space weather research activities to provide a world-leading forecasting system, help protect critical infrastructure, and support space situational awareness activities. This should include a dedicated Australian spacecraft constellation.

Box: Australian Space Weather Research

The Bureau of Meteorology's Space Weather Service (SWS) provides space weather predictions to the public and specialised services for a range of customers, the largest being Defence. It has been proactive in developing new products supporting a variety of sectors. The SWS also operates the Australasian regional warning centre and hosts the World Data Centre for Space Weather on behalf of the International Council for Science. Its forecasts are based on data assimilation and nowcasting and it engages in research through collaborations mostly with university groups. Although a small unit, the SWS was found by a 2014 external review to be "in the top tier of global space weather centres". The SWS sources data from its own and other Australian infrastructure and collaborating international organisations.

Ground-based space weather sensors are operated more or less independently by the SWS, the Australian Antarctic Division, DST Group (to support JORN operations), GA, and various university research groups. The latter includes over-the-horizon research radars operated by a consortium headed by La Trobe University, which are technology leaders in a global research radar network. Support for the various Australian observing networks depends on institutional priorities.

Australia's disjointed approach to space weather research contrasts with international efforts, such as the U.S. Center for Space Environment Modeling, and China's Meridian Space Weather Monitoring Network. The latter comprises a heavily instrumented ground sensor network monitoring the geospace environment along the 120° meridian extending from northern China across Australia and to Antarctica, and also along the 30°N parallel, plus sounding rockets. Data are analysed at China's Center for Space Science and Applied Research, informing China's space weather integrated model (SWIM) and multiple space weather prediction centres.

Box: Novel in orbit CubeSat surveillance SSA experiments

M2 is an Australian-technology capability demonstration and R&D platform for RAAF and in turn for Defence, with the primary purpose being optical and RF maritime surveillance as an example of indigenous space-based remote-sensing capabilities.

It incorporates in-house technology building blocks including optical telescopes; software defined radios; best-in-class fully-reprogrammable-in-orbit flight computers; CPU/FPGA/GPU-based on-board processing; formation flying technologies; attitude determination and control system; GPS and star trackers to assist navigation and pointing; intersatellite and ground-space radio and optical links.

The mission also carries an events-based neuromorphic optical sensor from Western Sydney University, a hosted attitude control payload for Technical University Munich, and an ionospheric aerodynamics experiment to validate the science needed to control and de-orbit propulsion-less spacecraft at and from higher orbits than previously thought possible.

M2 is designed as a 12U CubeSat which splits into two 6U halves to facilitate in orbit attitude control experiments based on different cross-sections. Further activities include space-based Space Surveillance employing its on-board technologies.

Successfully launched in March 2021, M2 represents the most significant Australian space technology capability to date, and will be a world-leading pathfinder for the Australian space sector.

3.3 Space for Health

Why is space medical and life science important?

Research in space medical and life sciences enables human space exploration but also provides important practical benefits to society. Australia has a unique advantage by pairing internationally acknowledged medical, health and behavioural science research with experience in delivering health services to unforgiving rural and remote environments, from the outback to Antarctic expeditions. Capitalising on these strengths opens the opportunity for Australia to contribute to international programs such as NASA's Artemis, and translate research outcomes to improve health outcomes in everyday life.

Space biomedical sciences expertise is a prerequisite for long duration crewed space missions and space tourism. As part of its Human Research Roadmap (HRR) NASA has identified 28 overarching medical risks for crewed spaceflight, mapping to 230 knowledge gaps. The risks include exposure to ionising radiation, cognitive and behavioural effects of spaceflight, physiological consequences of long term exposure to microgravity environments, and long term storage and stability of food and medications. As just one example, radiation exposure for an interplanetary mission to Mars substantially exceeds NASA's current permissible limits for exposure-induced death due to radiation carcinogenesis and associated risks[38]. Research to understand and ameliorate radiation exposure in space is closely related to research in radiation oncology settings to improve dose delivery, verification and outcomes to cancer patients. There are similar synergies between space medicine and life science R&D and practical benefits across other areas.

A survey conducted for this Plan by the Space Health and Life Sciences Working Group (see accompanying volume), identified specific areas of Australian expertise and mapped these to NASA

HRR knowledge gaps. Seventy-seven percent of survey respondents reported current or previous collaborations with international space agencies, most commonly NASA (30%), ESA (21%) and DLR (12%). A range of domestic capabilities can be developed or enhanced to support such international agency collaborations. These may include parabolic flight programs, head-down bed rest laboratories, short and long arm centrifuges, radiation laboratories, microgravity simulators, and hypobaric facilities. Establishment of a desert-based space analogue research program has the potential to supplement existing Antarctic analogue research to enhance understanding of psycho-social and human factors aspects of the risks identified.

There are clear opportunities and compelling reasons for development and growth of Australian space health and life sciences research, with benefits across three domains.

Contribute to international space missions and programs

Australia can contribute in meaningful and important ways to international space programs and missions. For example, the Centre for Medical Radiation Physics at the University of Wollongong is leading research in the development of microdosimeters for use in radiation therapy and space missions (see boxes), while teams at CSIRO's Health and Biosecurity unit, and Manufacturing unit, respectively lead medical image analysis research, and development of novel radiation shielding materials.

Many academic and clinical institutions around the country are involved in a wide range of space related disciplines, including fatigue and circadian physiology, somatosensory physiology, microgravity countermeasures, radiation microdosimetry and shielding, musculoskeletal effects of space flight, neurophysiology, nanotechnology, environmental monitoring, cellular biology, psychology/psychophysiology, and bioethics. Private industry is already collaborating with international space agencies, for example in the novel use of virtual reality for space applications, data analytics, wearable biomonitoring, and antimicrobial nanotechnologies. These existing areas of expertise position Australia well to expand its contribution to future human space flight programs through space medicine education, medical support for long-term exploratory missions, and developing countermeasures for the physiological challenges of space flight. In turn, collaborations with overseas partners will grow Australian capability and international profile. Australia can indeed play a key role in human spaceflight programs such as Artemis and Moon to Mars.

Radiation sensors for space and clinical applications

The Centre for Medical Radiation Physics at the University of Wollongong is internationally recognised as a leader in the field of radiation sensors for use in space exploration, medicine, aviation and homeland security. Director of the Centre, Prof Anatoly Rozenfeld, has patented a microdosimeter for use in space to protect astronauts and systems from hazardous radiation, a consequence of space weather. Supported by funding from ESA, the Centre is partnering with the Norwegian research organisation SINTEF to develop a tissue-equivalent sensor for real-time measurement of radiation at the cellular level. These activities are part of a very substantial research effort at the Centre focusing on semiconductor detectors and dosimeters for clinical applications in radiation protection, radiation oncology and nuclear medicine. The microdosimeters heading for space are also being tested in radiation oncology centres around the world where new radiation treatments are being used to treat cancer.

Accelerate biomedical technology

There has never been a better time to accelerate Australia's innovative biomedical technology industry. The importance of this sector and its potential to drive productivity and growth is recognised through the National Innovation and Science Agenda. There is a key intersection between space technologies and biomedical technologies through human spaceflight missions, but beyond this, space also provides a unique microgravity laboratory that can be used to develop novel biomedical technologies which can be commercialised purely for the benefit of human health.

This includes manufacturing of pharmaceuticals and food products in and suitable for space and hence austere and arid environments, and environmental engineering systems (for space life support systems) which can improve waste management, water purification and treatment, bioregenerative systems, air filtration, toxin monitoring, and biosecurity and infection control.

While Australian researchers are already active in many areas of space life and health sciences, they mostly have worked independently in small groups without the benefit of a national priority or framework (including Field of Research classification) to support the development of research, collaborations and partnerships domestically and internationally. This impedes the growth of research and translation of research into useful applications.

The first step in addressing this is endorsement of the three overarching enabling platforms proposed in this Plan: a national research priority in space science, a national capability in space, and a trusted voice advocating for space science.

It is also necessary to encourage collaboration between space health and life sciences disciplines and translation of research into useful applications. The newly formed Australian Human Research Institute for Space and Extreme Environments (AHRISEE) is an example of such a focal point and leadership role. The Institute's areas of focus include collaborative translational research in response to international space agency and industry challenges, space mission support, and Australian space life sciences education and training. The Institute can also support the Australian Space Agency in providing a point of liaison and coordination with the biomedical community and international agencies. Initial support to establish the Institute has come from the University of Tasmania, CSIRO, the Australian Antarctic Division, and the Tasmanian Government. In order to harmonise and grow activities at the national level the Institute requires a suitable commitment of ongoing support.

Leverage benefits for human health

The scientific spin-offs that arise from human spaceflight programs can provide substantial economic and public health benefits through improved health care, the development of novel technologies by private industry, and stimulation of the academic and research sector. Developing countermeasures for the physiological and mental challenges of space flight has direct practical application to Earth-based public health challenges and may result in breakthrough improvements to public health outcomes, particularly in elderly, underserved, remote and indigenous populations.

The areas of greatest benefit in the short term are likely to come from:

- bone density research for osteoporosis - suffered by over 6 million Australians over the age of 50 and costing $3.8 billion by 2022
- exercise development and reconditioning for people with musculoskeletal conditions - these conditions contribute 12- 14% of the total burden of disease in Australia
- sleep and circadian physiology research - inadequate sleep cost Australia an estimated $66 billion in 2016-17

- neuro-vestibular research for falls prevention - falls resulted in 1.4 million patient-days of hospital treatment in 2014-15
- miniaturization of medical diagnostics, sensors and technologies
- telehealth and remote medicine training and support - inhabitants of remote and very remote areas of Australia experience a total disease burden 1.4 times higher than major cities
- psychological care for isolated populations - bushfire and pandemic crises have highlighted the need for mental health support to physically and socially isolated populations
- antimicrobials to combat increasing antibiotic resistance
- space-hardened pharmaceuticals and increased efficiencies in agriculture.

Antarctica as a space analogue

The Scientific Committee on Antarctic Research (SCAR) Expert Group on Human Biology and Medicine sets priorities for research on, and healthcare of, humans in Antarctica involving the fields of biomedical sciences, social and behavioural sciences, and medicine. Areas of particular interest include research into the effects of isolation, cold, altitude and light and dark. The use of the Antarctic as a space analogue for human research has been of interest to the international polar medicine community for some time.

Australia's Antarctic Program uses "Life in a Freezer" to offer a hi-fidelity space analogue for Operational Medicine, Training and Research for "ICE" environments – Isolated, Confined and Extreme. Antarctic expeditioners can spend up to 9 months (March–November) without access to evacuation in the event of an emergency. In addition, there is limited sophistication of medical support. They live in small populations in shared habitats surrounded by an extreme environment adding to psychological stressors. These hazards are just as life threatening as those found in space and on other celestial bodies.

This challenging environment provides an analogue platform that has enabled Australian research in physiology, epidemiology, behavioural health and psychology, and photobiology. It has provided clinical and operational medicine and training for extreme environment, and advanced telehealth and other technologies for training and clinical support of isolated populations.

The Covid-19 pandemic has demonstrated the importance of even simple telehealth consultations and mental health services[xiv]. The capability needed to meet the comprehensive medical requirements of long duration space missions could revolutionise the efficacy and cost of virtual health delivery across all areas of Australia. This is an opportunity too important to ignore.

In order to maximise benefits to the domestic community and our opportunities to participate in international space programs, Australia should prioritise and grow research in existing areas of expertise:

- **Technology-based healthcare delivery,** training and clinical support for isolated, remote and extreme environments, including leapfrog telemedicine technologies for imaging, patient monitoring and AI diagnostics

- **Radiation**, to help solve a range of key knowledge gaps including cognition, behaviour and health.

[xiv] Over March 2020 to April 2021, $2.9 billion in Medicare benefits were paid for Covid-19 MBS telehealth services. Source: The Hon Greg Hunt MP, Minister for Health, 26 April 2021.

- **Microgravity,** in particular musculoskeletal and neuro-vestibular physiology, where the biggest population health benefit can be derived from innovation and where dedicated facilities, human centrifuge, head-down bed rest laboratory and parabolic flight would greatly enhance capability.
- **Life support systems**, photosynthetic bioregenerative environmental systems to provide innovative solutions to problems of agriculture and nutrition, water recycling, microbial countermeasures, and waste management.
- **Suborbital flight** physiology and safety, spinning-off into a potentially lucrative commercial space tourism market.
- **Analogue space research,** using a remote desert environment to explore the physiology and psychology of isolation and confinement, human factors and psycho-social risks. These are key NASA knowledge gaps but areas of Australian expertise could form a niche international strength.

Recommendation

A commitment of support to space life science research, including space medicine and human factors, engaging with international programs and providing translation of research to improve everyday life.

4. Space for the Future

'If you think in terms of a year, plant a seed; if in terms of ten years, plant trees; if in terms of 100 years, teach the people.' Confucius

The Australian space workforce

Skills gaps

Science, technology, engineering and mathematics (STEM) skills are essential for Australia's future workforce[39]. These are also core disciplines and skills for the space sector. Surveys and working group reports commissioned to inform this Plan, and other reports[40,41], point to workforce planning and development as the top strategic risk to the sustainable growth of the Australian space industry.

Australia's STEM workforce currently lacks the scientific, engineering and technical skills capacity to support our space needs[42]. Many of these require degree or higher level training in disciplines such as physics, mathematics, electronic and software engineering, and data science. There is also a need for skills in human aspects including human cognition, performance, decision-making, governance frameworks and engaging with space technology.

These capability gaps are mirrored in international jurisdictions, putting further pressure on our domestic supply. Agencies such as NASA and the UK Space Agency are reporting persistent skills shortages, lack of a STEM and HASS (humanities and social science) workforce, and concerns about a wave of generational retirements[43,44]. In 2018, 58% of Canadian space companies had difficulties hiring STEM personnel to the extent that positions went unfilled.

Defence is currently the largest entity in Australia's space sector. It has been obliged to develop strategies to grow its STEM workforce[45], including internships and in-house training of STEM graduates and postgraduates[46]. However, there are synergies between defence, government, industry and academia for building space capability, access to research and infrastructure, critical materials, need for standards, specialised skills and attracting staff[47]. Much specialist skills training is also performed on the job in industry locally or overseas.

Benchmarking projections of workforce requirements

The Canadian space sector has been building and operating spacecraft since 1962. In 2018 its workforce numbered just under 9,600 FTE, of which 61% were STEM qualified and 64% had a bachelor's degree or higher[48]. One third of the workforce comprised engineers and scientists. The space workforce was evenly divided between upstream (R&D, manufacturing, launch) and downstream (infrastructure, applications) sectors, and supported another 11,300 jobs in the broader economy.

The Australian Civil Space Strategy target is 20,000 new space-related jobs by 2030. Extrapolation against the structure of the Canadian space industry shows this will require at least 1,000 new space sector employees including around 330 new qualified scientists and engineers each year for a decade. This pipeline of new graduates must be in addition to meeting existing shortages. A small proportion of specialists may be recruited from overseas but mostly Australia will need to depend on recruiting domestic students currently at university or VET, or in secondary school and contemplating STEM career options.

Harnessing the talent pool

Our survey results reveal a mix of hesitancy and confidence about space sector careers. The most common concerns are lack of funding, instability of employment, and poor career prospects. On the other hand, most respondents believe their prospects of space-related employment are good to excellent, but (especially for younger people) often think these need to be pursued overseas. Mid- and later career women find this a barrier for family reasons. Only 19% of survey respondents were women, and one (0.5%) identified as indigenous. The proportion of female researchers in engineering and physical sciences is also just 19%[49] because 75% of girls of school and higher education age don't find STEM careers are of interest[50]. The VET sector overwhelmingly provides engineering-related training but women comprise only 8% of the VET STEM qualified workforce[51].

It doesn't have to be this way. An OECD report[52] points out that Russia and Ukraine have near gender parity in the space manufacturing sector, while in the UAE Space Centre and the South African Space Agency women form 40% and 39% of engineers and scientists respectively. The Australian astronomy community has targeted activities to increase public outreach and diversity, setting a goal for at least 33% participation by women across all levels of employment by 2025[53]. The proportion of women researchers in astronomy positions in Australia has risen from 21% in 2015 to 27% in 2019[54].

Can the university sector meet the needs?

Undergraduate completion data show that bachelor degree graduation rates in some space skills areas such as physics, areas of engineering, and geographical sciences have been decreasing and are well short of meeting space workforce demand. Completion rates in some other areas such as mathematics and electronic and computer engineering have been increasing but are also short of meeting future space workforce demand.

In response, some universities have developed new space science degree programs, specialised Masters programs[xv] and research initiatives[xvi]. Space industry focused centres are also emerging in Australian universities[xvii], and industry PhD scholarships and internships (e.g. CSIRO, SmartSat CRC). Various universities are also rapidly developing short courses and microcredential training aimed at stakeholder needs across the space sector (e.g. Swinburne, ANU, SmartSat CRC, University of South Australia in collaboration with the International Space University in France).

All these capabilities are small and discrete. Moreover, pandemic-related restrictions on international travel to Australia are also impacting the STEM workforce and the tertiary research and training sector[55]. Universities shed over 17,000 staff in 2020[56] with further phased reductions planned at many institutions. These will impact research and training in areas such as science, particularly for women on short-term contracts[57]. For example, two of Australia's three world-standard planetary science groups have been effectively disestablished.

Role of the VET sector

VET training provision is largely industry-led and there are few bespoke VET training courses. In the space industry, demand from either defence or inclusion of space-applicable occupations in national or state/territory skills needs lists helps guide training provision in VET. There are, at present, no space industry-specific courses listed on [myskills.gov.au.](myskills.gov.au) Some VET training options could be applicable to the space industry, such as robotics, electronics, and communication engineering and computer systems engineering.

[xv] RMIT, University of Southern Queensland, University of NSW Canberra
[xvi] e.g. Curtin University Space Science and Technology Centre, UNSW Canberra Space, UWA International Space Centre
[xvii] e.g. CUAVA training centre at University of Sydney, Swinburne Space Technology and Industry Institute, RMIT Space Industry hub, UNSW Australian Centre for Space Engineering

It is not currently known to what extent the space workforce requirements in Australia will be met by offering space-specific courses. However, in the UK technicians comprise around 20% of the space industry[58] while for Canada this is around 11%.

A national space workforce strategy

The above discussion shows that the Australia's STEM training and skills sector is currently incapable of meeting expected future demand for the space workforce.

Building this future workforce requires an overarching strategy to grow the skills pipeline. It should complement the *Defence Industry Skilling and STEM Strategy* (2019) and span the school, tertiary and industry sectors. A key plank of the ASA's Civil Space Strategy is the pillar *'Build future workforce: Partner in a vision to build an Australian space sector that inspires industry, researchers, government and the Australian community to grow the next generation of the space workforce'*. The Australian Space Agency should therefore carry lead responsibility for growing capacity, capability, and diversity of the space workforce.

Below we focus on three enablers for such a strategy.

Engagement: growing the STEM foundation

Relative to international benchmarks, performance of the Australian school system in core STEM subjects has been steadily declining for some years[59]. However, space exploration inspires, and space science can be a valuable vector to STEM engagement. The school level provides the largest audience to encourage young Australians with diverse backgrounds to pursue STEM and space-related studies. International space agencies understand that aspirational space missions and hands-on space-science themed activities are important motivators for young people to engage with STEM programs[60]. Accordingly they provide opportunities for students to watch, learn from and even participate in space-based research.

Various aspects of space science are included in State, Territory, and national curricula, but there are few dedicated facilities and teachers who are subject matter experts. Teachers seeking on-line space-related resources often use NASA sites and materials, which ignore the Australian context. The mission of the Australian Space Discovery Centre, located at Lot Fourteen in Adelaide, is to inspire the next generation of the space workforce, but it is not clear if this will include teaching and learning resources developed for the Australian curriculum, and explicit information on career options.

Programs to increase engagement in space studies have been developed by a variety of government groups, NGOs, industries, fee-for-service businesses, and individuals. While many of these may be excellent, this ad hoc approach is confusing, risks duplication of effort, does not provide for quality audit and evaluation of performance or outcomes, and does not ensure diversity and inclusion aspects are effectively incorporated.

Successful camps for high school students have operated for some years in South Australia (South Australian Space School) and Queensland (Australian Youth Aerospace Forum), and several small businesses offer space science expertise on a fee-for-service basis. CSIRO also provides extensive educational activities and resources related to space science engagement. One stand-out organisation, the Victorian Space Science Education Centre (VSSEC), uses space science content and examples which are fully integrated with the school curriculum.

The International Space Education Board (ISEB), founded in 2005, brings together ten space agencies with the aim of increasing STEM literacy and supporting the future space workforce needs of member countries. ISEB provides a range of education initiatives including specialised events and opportunities for students. Australia is the only ISEB member not represented by a space agency, this role instead being championed by the VSSEC, which is not tasked or resourced for such activity.

Space science as a STEM vector: VSSEC

The Victorian Space Science Education Centre, hosted on the campus of Strathmore Secondary College in Melbourne, is one of six specialist maths/science centres established more than a decade ago by the State Department of Education and Training. It uses space science as the teaching vector to introduce to basic concepts in mathematics, physics and chemistry in hands-on, scenario based contexts. VSSEC's signature program is a Mission to Mars, aimed mainly at students in years 7-9. All activities are fully integrated with primary and secondary curricula. VSSEC caters for around 15,000 face-to-face students annually but also provides on-line programs and professional development resources.

The Centre has achieved international recognition and is at the forefront of educational practice because of the way in which it combines a deep understanding of pedagogy (the science of teaching) with the teaching of science (and technology, engineering and mathematics). VSSEC represents Australia on the International Space Education Board, alongside nine space agencies including NASA, ESA, CNES and JAXA.

We identify the following actions to improve engagement in space-related and hence STEM topics at school level.

- **Mapping:** research to map the space science education ecosystem, to understand the gaps and the most successful levers, particularly as they relate to under-represented groups. This should include evaluation of the role of museums, observatories, planetariums, exhibitions, and science festivals such as COSPAR-K and National Science Week in contributing to space science education. Such mapping should also aim to build stronger connection, information sharing and coordination across Australia.
- **Commitment:** a national level commitment to developing, curating and providing curriculum-relevant Australian space-related material to stimulate STEM engagement, and related educator professional development resources. The materials should be diverse and inclusive, to ensure all students can see a career for themselves in space, and be developed in consultation with the Australian Science Teachers' Association (ASTA). Ideally this would include hands-on science-driven space-related projects, including participation in mission design (see below) with support from the Australian Space Agency.
- **Access:** such material is widely and freely accessible through a respected, suitably maintained portal, particularly to reach remote communities and students with a disability. Consideration should be given to how those on the low digital inclusion index can also access these resources.
- **Quality assurance and evaluation:** an evaluation plan is developed to support and empower space and education professionals to measure the effectiveness of their STEM outreach, in line with the Women in STEM Ambassador's *National Evaluation Guide for STEM Gender Equity Programs*[61], to improve programs and delivery.
- **Scope:** teaching resources and classroom activities highlight the breadth, cross-disciplinary and collaborative nature of space science activities.

- **Context:** Australian examples of space activity and achievement are used where possible, including Australian role models and leveraging the Australian Government's Girls in STEM Toolkit.

Retention and diversity: harnessing the talent pool

A survey of nearly 1,500 Australian scientists in May 2020[62] found that 16% of men and 22% of women were planning to leave the workforce, that there is a 17% wage gap for all sectors, and that one in five women had reported sexual harassment at least once in their careers. Women with postgraduate STEM qualifications earn significantly less than men, probably because they are more likely to be working part-time or not at all and providing unpaid childcare to their children[63]. They have also been disproportionately impacted by the COVID-19 pandemic[64]. The main impacts are increased workload, decreased productivity and decreased income, as women try to balance increasingly blurred work and family responsibilities. However, problems and solutions go beyond gender equity. For example, inflexible parental leave schemes impact paternity leave and affect family structures and workplace performance.

Australia is home to the world's longest established indigenous culture, which has a close affinity with the land and sky. Space-related infrastructure is increasingly being deployed across traditional homelands. However, indigenous peoples are under-represented in the space sector.

The benefits of diversity in the workforce are well known. The lack of representation of women and Indigenous Australians in STEM has been highlighted as a national problem by many groups, including the Australian Government and the Chief Scientist. The Women in STEM Decadal Plan developed by the Australian Academy of Science in collaboration with the Australian Academy of Technology and Engineering, identified strategies and actions to help address these inequalities through to 2030 and work is ongoing through the Women in STEM Ambassador. A global summary of policy instruments used by various jurisdictions to improve gender equity and STEM education in space-related fields is given in the OECD report.

The following additional recommended actions aim to improve retention, diversity, and inclusion in order to benefit the capacity and productivity of the Australian space workforce.

- Advocacy by senior leaders promoting engagement and role models of preferred practices, managed through a Diversity and Inclusion Office within the Australian Space Agency.
- Data collection and research supported by this Office on the experiences of people with diverse backgrounds in the space science and industry sector, in order to inform strategies.
- Encouraging adoption across the space sector of principles supporting equity, diversity, and flexible working environments. Suitable models may include the Gender Action Toolkit of the Centre for All-sky Astrophysics (CAASTRO)[xviii], the Science in Australia Gender Equity (SAGE) program, and recommended actions in the Academy of Science report *Impact of COVID-19 on women in the STEM workforce*.
- Ensuring digital accessibility and support is equally available to all.
- An award scheme, similar to the Pleiades Awards by the Astronomical Society of Australia, to recognise Australian space organisations which take active steps to promote equity and inclusion of all people, and to actively support currently marginalised groups.
- Encouraging space-related organisations to become Champions of the Women in STEM Decadal Plan, and support organisations advocating for gender and diversity inclusiveness, such as the Women in Space Chapter (WiSC) of the National Space Society of Australia. As part of this,

[xviii] http://caastro.org/gender-action-toolkit/

collaboration where appropriate with organisations such as the Australian Institute of Physics, the Space Industry Association of Australia, the Astronomical Society of Australia, and Astronomy Australia Limited.

Improving outcomes: cross-sector collaborative experiences

Universities are the engine-room for basic, enabling research, and the supply chain for the highly skilled workforce. However, Australia has a poor record of translating research to industry outcomes[65]. From the space perspective, a key factor that would improve this situation is a strategy to bring together disparate elements of the space sector to collaborate on challenging space missions and projects, from conception through to operation, to develop essential capability and infrastructure.

We identify the following actions which may be part of such a strategy.

- A program such as the Canadian CubeSat Project (see section 3.1) designed to grow innovation and capability through engaging tertiary students in developing scientifically valid CubeSat space missions. An Australian ground-based example is the Monash Nova Rover (see box).
- A program similar to NASA's Technology Transfer Program[66], which provides a central resource for technology access and commercialisation.
- A seed funding scheme supporting collaborative projects, for example with the Space Agency partnering on ARC linkage type grants. While the CRC program has similar objectives, it does not support new or innovative projects outside the scope of existing CRC partnerships.

Nova Rover

Monash Nova Rover is a team of Monash University students who have been designing, fabricating and testing Mars rovers in their Melbourne laboratory. Comprising (in 2020) almost 50 students (one third women) from Commerce, Design, Engineering, IT, Medicine and Science, the team has been taking its rovers to compete in the international University Rover Challenge (URC) since 2017. The machines are highly sophisticated, featuring autonomous navigation, a robotic arm, several cameras, a comprehensive sensor suite, and life detection capability.

URC is the world's premier robotic competition for tertiary students, held annually in the Utah desert. In order to qualify teams need to present a Science Plan, pass a Preliminary Design Review and a System Acceptance Review, and produce a detailed Financial Report. Nova Rover is an outstanding example of how space science empowers engagement with STEM technology, producing young scientists and engineers with skills to drive the innovation economy.

- A professional development and mentoring program to support career development for young space scientists and engineers across the academia-industry nexus. Many primes and government departments (e.g. Defence, CSIRO) already offer development opportunities but a program of national scope, with cross-sector focus and funded to defray industry participation costs, is needed to address workforce skills gaps[xix].
- Standardised IP agreements and other arrangements between state and Federal governments to reduce inefficiency and promote engagement, and a national framework to help protect domestic IP.

[xix] A pilot program of this nature has been funded by the Academy of Science's Theo Murphy Initiative for 2021-2.

- Removing the discrimination between university and industry-based R&D groups, who all need to develop IP to sustain and grow their activities. For example, the Canadian Space Agency regards academic organisations as core elements of the space workforce, contributing 20% of that workforce (almost all in STEM), 21% of registered patents, and engaging with international partners.
- Regular science-government-industry workshops to promote information sharing and collaboration[xx]. Pricing must allow student attendance.
- Mechanisms to encourage and reward staff flexibility between academia and industry (e.g. encouraging industry-based academic study leave; academic co-appointments for industry fellows)

Recommendation

An integrated national space innovation and education strategy, led by the Australian Space Agency, that spans the primary, secondary, tertiary, VET and industry sectors, and aims to grow STEM participation, improve career pathways, and improve industry outcomes, cognisant of the values of diversity and gender equity.

[xx] The biannual Space Forum run in Adelaide has not to date included a science focus, while the Avalon airshow is mostly a Defence event.

Appendix A

Abbreviations

ADF	Australian Defence Force
ARC	Australian Research Council
ASA	Australian Space Agency
BoM	Bureau of Meteorology
COPUOS	[United Nations] Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research, a member of the International Science Council
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CubeSat	A microsatellite based on a 10 x 10 cm size format, e.g. 3U = 30 x 10 x 10 cm, etc.
DST	Defence Science Technology (Group)
EO	Earth Observation
GA	Geoscience Australia
GDP	Gross domestic product
GEO	Geostationary orbit
GNSS	Global navigation satellite system
IoT	Internet of Things
ISRU	In situ resource utilisation
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MWA	Murchison Widefield Array
NCRIS	National Collaborative Research Infrastructure Strategy
OECD	Organisation for Economic Co-operation and Development
PNT	Position, navigation and timing
R&D	Research and development
SBAS	Satellite-based augmentation system
SDA	Space Domain Awareness
SouthPAN	Southern Positioning Augmentation Network, in effect SBAS for the Austalasian region
SSA	Space Situational Awareness
STEM	Science, technology, engineering and mathematics
STM	Space Traffic Management
TRL	Technology readiness level, a scale of 1-9 (basic research to fully operational)
WMO	World Meteorological Organisation

Appendix B

The Plan Process

This plan has been informed by the activities of several Expert Working Groups, listed below. Each working group comprised up to 10 expert members. Reports from these working groups appear in a separate volume of accompanying papers.

The plan document was developed by the Executive Working Group also listed below.

Broad community input to the plan was obtained through a number of mechanism: town hall meetings at the Australian Space Research Conference in October 2019 and the COSPAR conference in February 2021; calls for submissions in December 2020 and to the exposure draft in August 2021; and solicited peer review in December 2020 and August 2021.

All participants have given their time generously and freely, despite competing and challenging priorities. The views represented in this document do not necessarily reflect the views of, nor imply endorsement by, any individual or any working group members' affiliated organisations.

Executive Working Group

Prof Frederick Menk	Chair, National Committee for Space and Radio Science
Dr Brett Biddington AM	Principal, Biddington Research Pty Ltd
Adam Seedsman	Executive Director, Australian Space Agency
Dr Kimberley Clayfield	Leader, Space Technology Future Science Platform, CSIRO
Prof Phil Bland	John Curtin Distinguished Professor, Curtin University
Prof Stuart Phinn	President, Earth Observation Australia Inc. The University of Queensland
Imogen Rea	Department of Industry, Science, Energy and Resources

Expert Working Groups and Chairs

Capacity development	Louise Moes	Academy of Science
Communications technologies	Prof Bill Cowley	University of South Australia
Demographics	A/Prof Carol Oliver	University of NSW
Education, training & careers	Dr Sarah Baker	South Australia Department of Education
Planetary sciences	Prof Phil Bland	Curtin University
Positioning, navigation and timing	Prof Chris Rizos	University of NSW
Remote sensing and Earth observation	Prof Stuart Phinn and Prof Simon Jones	University of Queensland RMIT University
Space health and life sciences	A/Prof Gordon Cable AM	University of Adelaide
Space technology	Nick Carter	CSIRO Astronomy and Space Science
Space situational awareness and space weather	Dr Melrose Brown	University of NSW Canberra
The heliosphere	Prof Colin Waters	University of Newcastle

Development of this Plan was kindly supported by the Australian Academy of Science, and financial contributions from the Australian Space Agency, CSIRO Astronomy and Space Science, and the SmartSat Cooperative Research Centre.

Appendix C

Examples of current Australian space science activities.

- Development of innovative small research satellites, mostly as technology development vehicles, at many universities. All of these activities involve students.
- Space-based remote sensing to improve horticulture, livestock and irrigation management, forecasting and mapping, identify presence of pests and diseases, improve nutrient use efficiency and yields (University of New England and others)
- Development of user-friendly applications for visualising global and regional geophysical and geological data through time (consortium led by University of Sydney)[67]
- A partnership between DLR and La Trobe University to develop the DESIS hyperspectral camera, built by Teledyne Brown Engineering and operating on the ISS[68]
- Development of an optical space situational awareness sensor array spanning Australia (Curtin University and Lockheed Martin)
- Expertise in ionospheric physics in universities and DSTG underpinning development of the Jindalee Operational Radar Network (JORN), backbone of Australia's long range surveillance capability
- Using advanced physics and mathematics to image the far side of the Sun and improve understanding of disruptive solar events (Monash, Sydney, Newcastle universities)
- Using GNSS for geodesy applications to measure crustal deformation and kinematics, Earth orientation and rotation (e.g. GA, UNSW, ANU)
- Remote sensing of the atmosphere and surface (via radio occultation and reflectometry techniques), substantially improving weather forecasting (BoM, RMIT, UNSW)
- Precise gravity measurements from orbit to investigate sea level rise, floods, droughts and earthquakes (University of Newcastle)
- Investigation of superflares at other stars and possible effects on planetary habitability (USQ)
- Development of high speed microwave wave chips and circuits for advanced satellite communications (Adelaide University and local and international collaborators)
- Collaboration with DLR (German space agency) on optical and quantum communication capability (University of South Australia and ANU)
- Development of machine learning and data visualisation software for NASA's Perseverance Mars Rover Mission (QUT)
- Research on the world's oldest land-based fossils, in the Pilbara region, providing new insight on origins of life on terrestrial planets (University of NSW)
- Skinsuits to mitigate bone and muscle loss on long duration space missions, with potential application in everyday sedentary situations (RMIT with local and international partners)
- Expertise in advanced materials, space medicine and radiation physics at CSIRO, ANSTO and Wollongong University leading to internationally important research projects on radiation protection for space missions
- Using a Mars Analogue research facility at Arkaroola, South Australia, for field science and engineering, evaluation of exploration methodologies, education and outreach (various university groups and Mars Society of Australia)

References

[1] *Security legislation amendment (critical infrastructure) bill 2020*, Department of Home Affairs, November 2020
[2] See e.g. https://www.esa.int/About_Us/Ministerial_Council_2016/What_is_space_4.0; https://www.thalesgroup.com/en/worldwide/space/news/space-40-unlocking-value-digital-transformation
[3] *Australian Space Agency Charter*, Department of Industry, Innovation and Science, October 2018
[4] 2020 Defence strategic update, Department of Defence
[5] Sovereign industrial capability priorities are outlined in the *Defence Industry Capability Plan 2018*. A $7 billion commitment to build Defence's space capabilities to 2030 is outlined in the *2020 Defence Strategic Update*.
[6] *OECD handbook on measuring the space economy*, OECD Publishing, doi:10.1787/9789264169166-en, 2012
[7] *New Zealand space sector: its value, scope and structure*, Deloitte Access Economics, 2019 https://www.mbie.govt.nz/assets/new-zealand-space-sector-its-value-scope-and-structure.pdf
[8] *Investment in the Australian space sector*, KPMG, January 2020
[9] *Decadal plan for Australian astronomy 2016–2025 Mid-term review*, Academy of Science, 2020.
[10] *Measuring the economic impact of the space sector: Key indicators and options to improve data*, OECD, October 2020, https://www.oecd.org/innovation/inno/measuring-economic-impact-space-sector.pdf
[11] *Space industry skills gap analysis*, Technical report no. 5, SmartSat CRC, March 2021
[12] *Moving towards a high-tech future for Defence*, Australian Government, 2019; *2020 Defence Strategic Update*
[13] *Space exploration and the pursuit of scientific knowledge*, in: *The space economy in figures: how space contributes to the global economy,* OECD, 2019
[14] https://www.oecd-ilibrary.org/economics/oecd-handbook-on-measuring-the-space-economy_9789264169166-en
[15]*Ex ante assessment of economic and societal effects induced by space investments in a small emerging space country*. Proceedings of the International Astronautical Congress, Võõras M et al, IAC. 13. 10336-10345, 2013.
[16] *Spillovers in the space sector, a research report for the UK Space Agency*, London Economics, 2018
[17] *Return from public space investments, final report*, London Economics, 2015
[18] *A sustainable method for quantifying the benefits of NASA technology transfer*, Comstock, DA et al., AIAA Space Conference and Exposition, AIAA 2011-7329, 2011
[19] *The socio-economic impacts of space activities,* in: *The space economy at a glance*, OECD, 2019
[20] *Exploration, imagination, innovation: A new space strategy for Canada*, Minister for Innovation, Science and Economic Development Canada, 2019
[21] *Projected exploration missions 2020-2030*, Bryce Space and Technology, August 2020
[22] Artemis III science definition team report, NASA/SP-20205009602, 2020
[23] http://sserviaustralia.org/
[24] *CubeSat array for detection of RF emissions from exoplanets using inter-satellite optical communicators*, de Kok et al., IEEE Aerospace conference, doi:10.1109/AERO47225.2020.9172296, 2020
[25] 2020 Defence strategic update, Department of Defence
[26] *Economic study into an Australian continuous launch small satellite program for Earth observation*, Delloitte Access Economics, 2021
[27] *Measuring the economic impact of early bushfire detection*, Biddle N, et al., ANU Centre for Social Research and Methods, March 2020
[28] *AusCalVal, Establishing Australia as a global leader in delivering quality assured satellite Earth observation data*, Earth Observation Australia, FrontierSI and SmartSat CRC, May 2021
[29] *Investment in the Australian space sector*, KPMG, January 2020
[30] *The impact of quantum technologies on secure communications*, Clark RC et al., ASPI Special Report, April 2021
[31] *An interplanetary network enabled by SmallSats*, Velazco J, 2020 IEEE Aerospace Conference, pp. 1-10, doi: 10.1109/AERO47225.2020.9172696, 2020
[32] *Security Legislation Amendment (Critical infrastructure) Bill 2020*, Parliament of Australia, December 2020

[33] *International collaboration within the United Nations Committee on Peaceful Uses of Outer Space: framework for international space weather services (2018-2030)*, Mann, IR et al., Space Weather, **16**, doi:10.1029/2018SW001815, 2018
[34] *Using the aa index over the last 14 solar cycles to characterise extreme geomagnetic activity*, Chapman, SC et al., Geophys. Res. Lett., **47**, doi:10.1029/2019GL086524, 2020
[35] *Kessler syndrome: System dynamics model*, Drmola J and T Hubik, Space Policy, **44-45**, doi:10.1016/j.space.pol.2018.03.003, 2018
[36] *Carbis Bay G7 summit communique*, Section 35, https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/13/carbis-bay-g7-summit-communique/, 13 June 2021
[37] *The Sun is less active than other solar-like stars*, Reinhold, T, et al., Science, **368**, doi:10.1126/science.aay3821, 2020
[38] *How Safe Is Safe Enough? Radiation Risk for a Human Mission to Mars,* Cucinotta et al., PLOS One, doi:/10.1371/journal.pone.0074988, 2013; see also NASA RFI *On the development of countermeasures to mitigate the risk of space radiation induced carcinogenesis, degenerative disease, and behavioral cognitive defects,* Solicitation No. 80JSC020L0006, August 2020
[39] *Science, technology, engineering and mathematics, Australia's future*, Chief Scientist, 2014, www.chiefscientist.com.au
[40] *Investment in the Australian space sector*, KPMG, January 2020
[41] *Submission to the Inquiry into Developing Australia's Space Industry,* Space Industry Association of Australia, 2021
[42] *Space industry skills gap analysis*, Technical report no. 5, SmartSat CRC, March 2021
[43] *2019 Report on NASA's top managment and performance challenges,* NASA Office of Inspector General, November 2019
[44] *Space Sector Skills Survey 2020*, United Kingdom Space Agency, www.bmgresearch.co.uk
[45] *Moving towards a high-tech future for Defence: Workforce strategic vision underpinned by Science, Technology, Engineering and Mathematics 2019-2030,* Department of Defence, 2019.
[46] *Defence industry skilling and STEM strategy*, Department of Defence, 2019
[47] *Action Plan on synergies between civil, defence and space industries*, European Commission, 2021
[48] *State of the Canadian space sector report 2019*, Canadian Space Agency ISSN: 2369-6338, 2019
[49] https://dataportal.arc.gov.au/ERA/GenderWorkforceReport/2018/pages/section2/index.html?id=gender-by-fields-of-research
[50] *STEM equity monitor*, Department of Industry, Science, Energy and Resources, 2021, https://www.industry.gov.au/data-and-publications/stem-equity-monitor
[51] *Australia's STEM workforce*, Office of the Chief Scientist, July 2020
[52] *The space economy in figures, how space contributes to the global economy*, OECD, 2019
[53] *Australia in the era of global astronomy. The decadal plan for Australian astronomy 2016-2025*, National Committee for Astronomy, 2015
[54] *Decadal plan for Australian astronomy 2016-2025 Mid-term review*, National Committee for Astronomy, 2020
[55] *Interim report of the inquiry into Australia's skilled migration program*, Joint Standing Committee on Migration, Canberra, March 2021
[56] Media release, Universities Australia, 3 February 2021
[57] https://www.science.org.au/sites/default/files/rrif-covid19-women-stem-workforce.pdf
[58] *Space for technicians?: An analysis of technician duties, skills and training in the UK space industry*, Lewis, P. A., SSRN Electron. J., doi:10.2139/ssrn.2861985, 2016
[59] *Australia 2030: Prosperity through innovation*, Department of Industry, Science, Energy and Resources, 2017.
[60] https://www.nasa.gov/mission_pages/station/research/news/b4h-3rd/ge-inspiring-youth-with-space-science; https://www.nasa.gov/stem
[61] https://womeninstem.org.au/national-evaluation-guide/
[62] *Professional Scientists' Employment and Remuneration Report*, Professional Scientists Australia, October 2020
[63] *STEM equity monitor data highlights 2021*, Department of Industry, Science, Energy and Resources, 2021
[64] *Impact of Covid-19 on women in the STEM workforce: Asia-Pacific*, Australian Academy of Science, 2021
[65] *Performance review of the Australian innovation, science and research system*, Innovation and Science Australia, 2016

[66] Technology.nasa.gov
[67] Earthbyte.org
[68] https://www.engineersaustralia.org.au/Event/fighting-bushfires-space-story-unique-australian-technology-international-space-station